The resolved stellar populations of M32

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Chapter 1

Introduction

In the early 1920s, E. Hubble discovered that some objects, then called nebulae, were outside of the Milky Way and therefore it was recognized that galaxies other than our own existed. His discovery fundamentally changed the view of the Universe, which by then was believed to consist solely of the Milky Way. Hubble was the first one to classify galaxies according to their morphology in optical light. He divided galaxies into two main types: ellipticals and spirals. The former appear on the sky as smooth, round and almost featureless systems, without signs of a disk and dust lanes. The spirals, on the other hand, have very bright spiral arms, outlined by clumps of bright hot stars and the compressed dusty gas from which these stars are formed. The Hubble classification system, although purely morphological, remains widely used to the present day. We now know that there are real structural differences between ellipticals and spirals. These differences suggest that different physical processes were involved in the formation and evolution of these galaxies.

Elliptical galaxies are the most massive stellar systems in the local Universe. Moreover, they represent a predominant fraction of its total stellar mass. Thus, understanding their formation and evolution is crucial to improve our understanding on galaxy formation and evolution in general. Detailed studies of the stellar populations in elliptical galaxies should provide the most straightforward means of testing their formation scenarios.

In this thesis we investigate the stellar populations of a particular elliptical galaxy, Messier 32 (M32), whose proximity allows us to study its individual stars with great detail. This work not only significantly improves our knowledge on the stellar populations of M32 but also provides an unprecedented rich data base to empirically test models that are used to decipher the star formation history of more distant elliptical galaxies. We discuss the properties of ellipticals as well as the current ideas about their formation and evolution (Sec. 1.1). The tools employed to study their stellar populations are reviewed in Sec. 1.2 followed by a brief summary of the properties and stellar populations of M32 (Sec. 1.3). We conclude this chapter by drawing an outline of this thesis (Sec. 1.4).

1.1 Elliptical galaxies

Elliptical galaxies are apparently simple and rather homogeneous stellar systems with a continuously declining brightness distribution. Their surface brightness profile $I(r)$ can be described remarkably well with Sérsic functions $\log I(r) \propto r^{1/n}$ (Sérsic 1968; Caon et al. 1993; Kormendy et al. 2009), where n is the only free parameter and it is called called Sérsic index. Hubble subclassified ellipticals according to their apparent ellipticity. In this scheme, ellipticals are denoted by E_n where $n = 10(1 - b/a)$ and b/a is the apparent flattening. In spite of being useful for classification purposes, it has been shown that virtually no physical characteristics of ellipticals correlate with the apparent ellipticity (Kormendy & Djorgovski 1989), although *deviations* from ellipticity do correlate with their physical properties.

Although elliptical galaxies look like simple objects on the sky, several detailed studies revealed that they are rather complex systems (see review by Kormendy et al. 2009, hereafter K09 and references therein), covering a huge range of luminosity and light concentration. Ellipticals can then be broadly divided into two main types with different structures, which suggests that they originated by a number of different processes:

(1) Giant (large and bright) ellipticals are slow anisotropic rotators and they have triaxial intrinsic shapes. In general they tend to be less flattened (E1.5) and show cores and boxy-distorted isophotes. Their surface brightness profiles are better described by Sérsic indices $n > 4$.

(2) In contrast, normal and low-luminosity ellipticals rotate rapidly, they are relatively isotropic, with oblate-spheroidal intrinsic shapes, and more flattened (E3). They are coreless and have disky-distorted isophotes. Their surface brightness profiles over large radial intervals are better described by Sérsic indices $n < 4$.

Elliptical galaxies show surprising regularities in their global properties, in spite of their large range of sizes and structural differences, and follow several empirical scaling relations, i.e. correlations between two or more observable parameters. One such relation is the "fundamental plane": the effective radius r_e of the light distribution, the central velocity dispersion σ_0, and mean effective surface brightness $\langle I_e \rangle$ lie in a tilted plane in parameter space $r_e \propto \sigma^{1.24} \langle I \rangle_e^{-0.82}$ (e.g., Djorgovski & Davis 1987; Faber et al. 1987; Dressler et al. 1987; Djorgovski et al. 1988; Djorgovski 1992; Bender et al. 1992; Jorgensen et al. 1996). This is a consequence of the virial theorem and the fact that ellipticals are nearly homologous over a wide range in luminosities L. The scatter in this correlation is similar to the parameter measurement errors (Saglia et al. 1993; Jorgensen et al. 1996). The Faber-Jackson relation $L \propto \sigma_0^4$ (Faber & Jackson 1976), the color-magnitude relation (bluer colors for fainter galaxies, Visvanathan & Sandage 1977), and the mass-metallicity relation (more massive galaxies being more metal-rich, Trager et al. 2000a) are other examples of the scaling relations of ellipticals (See Fig. 1.1). These tight scaling relations are believed to hold important clues to the formation and evolution of elliptical galaxies.

A perhaps even more relevant characteristic about ellipticals is that they show fundamental differences with spirals and also with spheroidals (or dwarfs). These

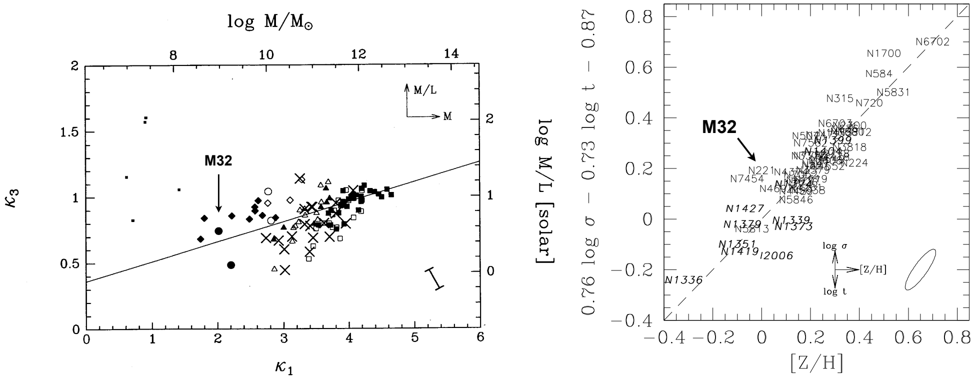

Figure 1.1: Scaling relations followed by ellipticals. Left panel: Edge-on projection of the fundamental plane for a sample of ~ 100 elliptical plus bulge of spiral galaxies from Bender et al. (1992). κ_1 and κ_2 are parameters from a coordinate system chosen to emphasize the fundamental plane while retaining physically meaningful variables. The values of the corresponding physical parameters are given in the opposite sides of the figure. Right panel: Mass-metallicity relation for a sample of ~ 50 early-type galaxies from Trager et al. (2000a). The ellipse indicates the size of the errors. M32, the subject of study in this thesis is indicated in both panels.

differences are most clearly seen in correlations between central properties, but they are also evident in global properties (see e.g., Kormendy 1987; Binggeli & Cameron 1991; Bender et al. 1992, 1993; K09). Fig 1.2 clearly shows that ellipticals lie on a distinct sequence from spirals and spheroidals. K09 using an accurate photometric sample of elliptical galaxies showed that their luminosity function is approximately bounded at low luminosities by M32 and at high luminosities by M87.

1.1.1 Formation and evolution

Since elliptical galaxies are predominantly old, they are 'fossils' of the earlier Universe. They represent at least 50% of the total stellar mass in the local Universe (Schechter & Dressler 1987; Gallazzi et al. 2008). Thus, understanding their formation and evolution is crucial to understand how galaxies form and evolve in a more general cosmological context.

Due to the seemingly simple nature of ellipticals, the so-called "monolithic collapse" scenario (Eggen et al. 1962) was originally adopted to explain the formation of these galaxies. In this scenario, galaxies form in a single intense burst of star formation in the early universe (at redshifts $z > 5$), followed by passive evolution of their stellar populations to the present day (Partridge & Peebles 1967; Larson 1975). This formation mechanism can successfully explain the tightness of the fundamental scaling relations of ellipticals, like the color-magnitude relation and the fundamental plane, as well as the evolution of those relations as a function of red-

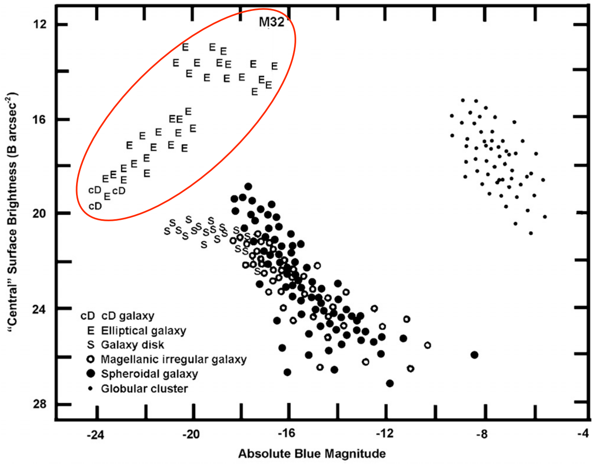

Figure 1.2: Correlations between the total absolute magnitude and central surface brightness for ellipticals, spirals, spheroidals (or dwarfs) and globular clusters from Kormendy et al. (2009). It is clear that the distribution of ellipticals (inside the oval) is disjoint from that of spirals and spheroidals. M32 is one of the lowest-luminosity true ellipticals.

shift (Kodama et al. 1998; van Dokkum & Stanford 2003). However, this model has been challenged by a more complex formation scenario.

Toomre & Toomre (1972) suggested that elliptical galaxies form in violent major mergers of massive disk galaxies that often include gas dissipation and star formation episodes. This second formation scenario was further study by using detailed numerical simulations (Toomre 1977; Farouki & Shapiro 1982; Negroponte & White 1983; Joseph & Wright 1985; Schweizer 1990; Kauffmann et al. 1993; Steinmetz & Navarro 2002). These studies show that merger progenitors usually contain gas which is driven to the galactic center thanks to gravitational torques (e.g. Barnes & Hernquist 1996, 1991) subsequently generating starbursts (e.g. Mihos & Hernquist 1994, 1996). This merger formation scenario was rapidly attractive and preferred by theorists since it appears to be a natural consequence of the hierarchical structure formation process predicted by the cosmological cold dark matter (CDM) paradigm (Blumenthal et al. 1984). In this paradigm, small primordial fluctuations whose densities are higher than the nearly-uniform density field of the early Universe will collapse and grow gravitationally, forming bound objects known as dark matter halos. The structure formation is then hierarchical: small objects form first and subsequently merge together to form larger structures. Within this scenario, galaxies form when gas cools and and condenses inside dark matter halos (White & Rees 1978) and continue growing hierarchically through the accretion of smaller objects. Over several years, observational evidence has demonstrated that interactions and mergers between galaxies are indeed a common phenomenon at high redshifts not surprisingly affecting the population of elliptical galaxies in the local Universe. For instance, Schweizer & Seitzer (1992) found evidence of bluer colors in elliptical galaxies suggesting a merger-induced recent star formation activity. Later studies using absorption-line indices have showed that a significant fraction of cluster early-type galaxies has undergone recent episodes of star formation (Schweizer et al. 1990; González 1993; Barger et al. 1996; Schweizer et al. 1990; Trager et al. 2000a). Additional indications of this recent activity have also been detected in high redshift early-type galaxies using colours (Menanteau et al. 2001; van de Ven et al. 2003) and absorption and emission line diagnostics (Treu et al. 2002; Willis et al. 2002). These observations have posed a challenge to the monolithic formation scenario. Another important result supporting the idea that at least a part of the ellipticals are formed in a hierarchical way, via the accretion and merger of smaller building blocks, is that the stellar mass of the red galaxy population increases by a factor of 2 since $z \sim 1$ (Bell et al. 2004; Brown et al. 2007; Faber et al. 2007).

The hierarchical formation scenario implies that galaxies are the final products of different merger histories in which, for example, different progenitor morphologies and star formation histories, and encounter geometries produced a variety of different results. As previously mentioned, the remarkable structural regularities observed in the final outcome of ellipticals, as well as the departures from them provide us with a profitable way to study galaxy formation. By combining data from a variety of different observations of early-type galaxies in the Virgo Cluster, K09 demonstrated that Sérsic functions fit most ellipticals remarkably well, and that local departures from these fits, as well as correlations involving the fit parameters, are diagnostic of galaxy formation mechanisms. K09 suggested that core ellipticals, i.e large ellipticals with total absolute magnitudes $M_{VT} \leq -21.66$ that have cores (missing light at small radii from the inward extrapolation of their Sérsic profiles), formed in dissipationless (“dry”) mergers since cores can be scoured by binary black holes (BHs) formed in such mergers: BH binaries form naturally in “dry” mergers of galaxies, their orbits decay and the binaries get harder flinging stars away. These stars, that are either deposited into a large volume at large radii or are ejected, have little effect on the galaxy outer profile. Since stars are removed from the small volume close to the BHs, the central surface brightness of the galaxy decreases generating a core. On the other hand, they suggested that all faint coreless ellipticals, i.e. ellipticals with $-21.54 \leq M_{VT} \leq -15.53$ which were found by K09 to have extra light at the center above the inward extrapolation of the outer Sérsic profile, are the result of dissipative (“wet”) mergers processes. In simulations of “wet” mergers (e.g., Mihos & Hernquist 1994), the gas dissipates, falls toward the center and undergoes a starburst generating a compact stellar component that, as in K09 observations, is distinct from the Sérsic profile of the main body of the elliptical. Although ellipticals with extra light also contain supermassive BHs, K09 suggest that the starburst swamped core scouring by binary BHs. Thus, they interpret the extra light components as a signature of formation in dissipative mergers. K09 also suggest that distinctions between the two kinds of ellipticals may be related to the number of mergers that shaped the systems. It is interesting to note that merger simulations (Hopkins et al. 2009b,a,c, 2008b,a) have reproduced the different properties of core and extra light ellipticals obtained by K09.

There is also evidence for a mass-dependent evolutionary history of ellipticals, such that the star formation histories of more massive elliptical galaxies peak at higher redshifts ($z \approx 5$) than lower mass systems; less massive ellipticals have star formation histories that peak at progressively lower redshifts and are extended over a longer time interval. This scenario, known as 'downsizing' and originally proposed by Cowie et al. (1996, see also Trager et al. 1993), is supported by both observations (Bell et al. 2005; Faber et al. 2005; Nelan et al. 2005; Thomas et al. 2005a; Bernardi et al. 2006; Noeske et al. 2007; Santini et al. 2009) and simulations (De Lucia et al. 2006; de Rossi et al. 2007; Fontanot et al. 2009). Results from semi-analytic models (De Lucia et al. 2006) show that an apparent 'downsizing' in the formation of ellipticals is not in contradiction with the hierarchical paradigm, as has often been interpreted. On one side, they find that the stars in more massive ellipticals are on average older than those in their less massive counterparts, i.e. the *formation times* of more massive ellipticals are earlier, reflected in the downsizing scenario. On the other side, they find that massive ellipticals assemble in a single object at much lower redshift than when their stars are formed and moreover, more massive galaxies assemble later than less massive ones. Thus, the *assembly history* of ellipticals is hierarchical in contrast to the formation history of the stars themselves.* These semi-analytic models of galaxy formation do predict anti-hierarchical star formation histories for ellipticals in a Λ-cold dark matter (ΛCDM) universe even though the assembly of these galaxies is indeed hierarchical.

In spite of the tremendous work both on the theoretical and on the observational sides, there are still unsolved issues concerning the theories for the formation of elliptical galaxies. One of the best approaches to test the theoretical models and decipher the star formation history (SFH) and evolution of these galaxies is to study in detail their stellar content. This is discussed in the next section.

1.2 Stellar populations

Stars have imprinted evolutionary parameters such as age and metallicity and thus provide a fossil record of the SFH and evolution of a galaxy. According to their proximity, elliptical galaxies can be either studied from their integrated light and/or observations of their individual stars. However the latter, although more powerful, has only been possible for a handful of nearby ellipticals, including the galaxy studied in this thesis. In this section we discuss the diagnostic tools employed to study both unresolved and resolved stellar populations and what we have learned about the stellar populations of ellipticals up to now.

1.2.1 Unresolved stellar populations

In general, the only means available to study the stellar populations of elliptical galaxies is their spectral energy distribution (SED) which possesses contributions from all their stars, having a range of metallicities and ages. The large distances

* De Lucia et al. (2006) define the *formation redshift* as the redshift at which 50% (or 80%) of the stars that make up the galaxies at redshift zero are already formed. Their *assembly redshift* is defined as the redshift at which 50% (or 80%) of the final stellar mass is already contain in the galaxy.

of these galaxies in combination with their high surface brightnesses prevent detection of their intrinsically fainter individual stars limiting our knowledge about their stellar populations (see however 1.2.2). As a consequence, we rely strongly on unresolved stellar population models to learn about their SFHs. These models, introduced in the pioneering work by Tinsley (1972), are used to interpret the integrated light of galaxies and estimate their ages and metallicities. Since the spectra of galaxies possess contributions from all their stars, problems such as the non-trivial degeneracy between age and metallicity, especially observed in old populations such as those that dominate the masses of elliptical galaxies, have to be taken into account to properly determine the stellar parameters of the observed galaxy. Worthey (1994) established a possible way to tackle this issue by constructing models that use information from particular pairs of line-strength indices to break the age–metallicity degeneracy (building on previous work by, e.g., Rabin 1982). Based on this idea, and thanks to various improvements in, e.g., stellar evolution and spectral libraries and model atmospheres, there are currently several stellar population models that provide predicted line-strength index values of a single stellar population (SSP) (e.g., Bruzual & Charlot 2003; Thomas et al. 2003; Vazdekis et al. 2010). A comparison of these predicted values with those measured from an observed galaxy's spectrum determines the age and metallicity of the stars in that galaxy. Because the determination of these properties are based on SSP models, i.e. stars of the same single age and metallicity, these are called SSP-equivalent age and metallicity. Serra & Trager (2007) and Trager & Somerville (2009) investigated how these SSP-equivalent parameters relate to the average properties of galaxies using models of composite stellar populations. They found that the derived SSP-equivalent age of a galaxy depends primarily on the age of its younger population and the mass fraction between the different constituent populations, whereas the SSP-equivalent metallicity mostly depends on the metallicity of the old population. The SSP-equivalent age, moreover, is simply a Balmer-line-weighted age and should not be interpreted as the age of the bulk of stars in a galaxy.

The use of these more sophisticated models together with the acquisition of better and larger amounts of data have improved our knowledge on the stellar populations of ellipticals. The initial assumption that ellipticals are composed of a simple, old stellar population (Baade & Gaposchkin 1963) has dramatically changed (see e.g. Faber et al. 2007; Renzini 2006). Ellipticals are now known to be complex systems, with a variety of different stellar populations. In general terms, elliptical galaxies are dominated by old and metal-rich stars with a small amount of cool gas and thus very few young stars. A wide spread in their stellar ages has been found by several authors (e.g., González 1993; Trager 1997; Gallazzi et al. 2006). It was later found that a fraction of ellipticals have recently formed stars (Yi et al. 2005; Kaviraj et al. 2007) and intermediate-age populations are now commonly detected in ellipticals (Graves et al. 2007; Schawinski et al. 2007; Mármol-Queraltó et al. 2009). In addition, radial metallicity and/or age gradients are usually observed (e.g. González 1993; Davies et al. 1993; Sánchez-Blázquez et al. 2006; Tortora et al. 2010). It has also been noticed that, according to their type, ellipticals have different stellar populations: (1) Giant ellipticals have mostly old stellar populations and are enhanced in α elements (e.g. Worthey et al. 1992), whereas (2) lower-luminosity ellipticals generally are made of younger stars and their stellar populations are less enhanced or even Solar in α element abundances (see Jorgensen 1997; Trager et al. 2000a; K09 and references therein).

1.2.2 Resolved stellar populations: Color-Magnitude diagram analysis

In the 1940s, W. Baade observed, for the first time, individual stars in M31 and its companions M32 and NGC 205 (Baade 1944). This pioneering work initiated the field of resolved stellar populations, which has been a subject of continuing interest since then. The study of the individual stars in galaxies is the best and most direct way to understand their formation and evolution. An important requirement to perform this kind of analysis is the proximity of the galaxy under study. Thus, mostly galaxies in the Local Group (LG) can be studied in such a way. Unfortunately, there is a lack of giant ellipticals in the LG which limits our knowledge about their populations. Although there have been studies of the resolved giants near the tip of the red giant branch (RGB) in nearby ellipticals outside the LG (see, e.g., Sakai et al. 1997; Harris et al. 1999; Harris & Harris 2000; Gregg et al. 2004; Rejkuba et al. 2005), observations of the intrinsically fainter stars are needed in order to obtain the complete SFH of a galaxy (see below). The galaxy studied in this thesis, M32, although a low-luminosity galaxy, is the nearest elliptical for which we can resolve its individual stars to fainter magnitudes. Therefore, a more detailed study of its resolved stellar populations is possible.

The best tool to learn about the stellar populations of a galaxy is the color-magnitude diagram (CMD) of its individual stars. This is because the location of any star in a CMD is uniquely related to its mass, age and chemical composition. From applying stellar evolution theory to a CMD we can disentangle directly these evolution parameters. Moreover, the positions of stars in these diagrams represent the evolutionary sequences of stellar populations, which provide information about the SFH of a galaxy. However, some of these sequences are specifically sensitive to age and/or metallicity. Because different evolutionary phases populate different regions in a CMD, some of them are more informative than others. For instance, the best age indicator of a galaxy is the main sequence (MS) and in particular the main-sequence turnoff (MSTO); i.e. the point at which hydrogen burning stars have exhausted the hydrogen fuel in their cores. Due to the fact that, in this phase, the age is related to the luminosity and moreover stars obey a well-known mass-luminosity relation, there is a direct conversion of the MSTO's information into the SFH of a galaxy. In addition, the subgiant branch (SGB), the evolutionary phase between the MS and the RGB, defines another useful age indicator. The luminosity of both the MSTO and the SGB fade as the age of the system increases. Later evolutionary phases, namely the RGB, the horizontal branch (HB), the red clump (RC) and the asymptotic giant branch (AGB) are not such accurate age indicators

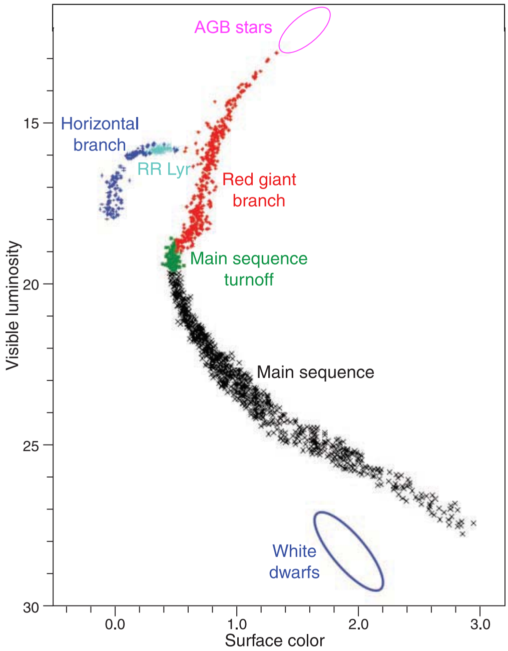

Figure 1.3: A schematic CMD for a typical globular cluster showing the location of the main evolutionary phases from Krauss & Chaboyer (2003). The visual luminosity of the stars is measured in V-band magnitude and the surface color in $(B-V)$. Some of these CMD features are very useful age indicators, as the main sequence turnoff. The horizontal branch indicates the presence of stars older than 10 Gyr, whereas asymptotic giant branch (AGB) stars indicate the presence of intermediate-age stars. The red giant branch (RGB), on the other hand, is a good metallicity indicator.

since their CMD positions are influenced by several factors (see e.g. Salaris & Cassisi 2005). The RGB, on the other hand, is more sensitive to the metallicity of the system. Nonetheless, these later phases are indicative of the presence of populations older than a some minimum age and are extremely useful when galaxies are too distant to have their MSTOs observed. For example, HB stars are always older than 10 Gyr, RGB stars are at least 1-2 Gyr old, and AGB stars are older than 100 Myr. Fig. 1.3 shows a schematic CMD showing the location of the principal stellar evolutionary sequences.

For decades, ages of stellar systems were determined by fitting isochrone-fittings to CMDs, in particular to the main sequence. This is an appropriate technique to study simple stellar populations, i.e. coeval stars with the same chemical composition, such as those find in stellar clusters, but clearly cannot be used to interpret the composite stellar populations present in galaxies. In galaxies various generations of stars, with different metallicities and ages, contribute to the appearance of the observed CMD. Thus, a new method to obtain the SFH of galaxies needed to be developed. The strong dependence of the CMD morphology on the SFH (see Fig. 1.4) is the key of the well-known synthetic CMD method, which consists in comparing the observational CMD of a galactic region with synthetic CMDs (see e.g., Tosi et al. 1991; Bertelli et al. 1992; Tolstoy & Saha 1996; Aparicio & Hidalgo 2009, for detailed descriptions of different procedures). The synthetic CMD method determines the variation of the SFR within the look-back time that can be reached by the available photometry. The direct observation, with accurate photometry, of the galaxy's oldest MSTO is necessary for the complete derivation of

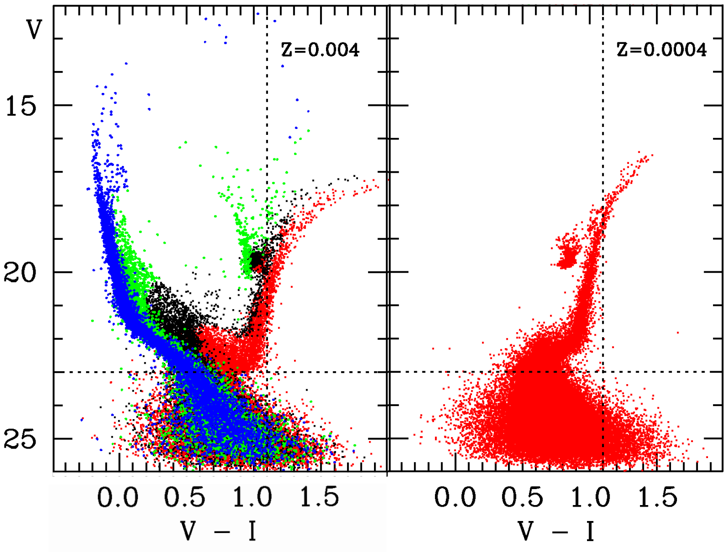

Figure 1.4: The effect on the CMD's morphology of different SFHs for an hypothetical LG galaxy with typical HST/WFPC2 photometric errors. The constant metallicity assumed is indicated in each panel and different colors correspond to different age intervals. Note that these metallicities differ by a factor of 10. Left panel: A constant SFR from 13 Gyr ago to the present epoch plus a 10 times stronger burst added in the last 20 Myr. Right panel: Old SFH with an episode of SFR from 13 to 10 Gyr ago. The dotted lines are drawn to help visualize the differences. From Tolstoy et al. (2009).

its SFH. The method does not provide unique solutions but significantly reduces the possible SFH scenarios. Due to both the intrinsic crowding and distance of the examined galaxy, and to the instrumental capabilities, it is not always possible to exploit all the information contained in a CMD. When the oldest MSTOs are not available, which is the case for most of the galaxies, evolved stars can be used very profitably to obtain information about the SFH, although with higher uncertainty and/or within shorter look-back times. Quantitative and qualitative indicators can be combined and complement each other to study the SFH of a galaxy (see Chapter 2, 3). Thanks to the capabilities of the *Hubble Space Telescope* (HST), launched in 1990, it was possible to resolve individual stars in many galaxies in the LG to unprecedented (and still unequalled) levels of faintness, distance and crowding (see e.g., Brown et al. 2006; Barker et al. 2007; Monelli et al. 2010). These studies found that the SFH not only differs significantly from one galaxy to another, but also according to where one looks within the same galaxy (see review by Tolstoy et al. 2009).

Finally, among the different types of stars that can be resolved in nearby galaxies, the RR Lyrae variables are particularly important since they can also indicate the presence of an ancient population. RR Lyrae variables are low mass ($0.6 - 0.8\,\mathrm{M}_{\odot}$) central He burning stars located on the HB evolutionary phase. Knowledge of their properties provides important information on their parent stellar populations: their mere presence is indicative of a ancient stellar population, as ages older than ~ 10 Gyr are required to produce RR Lyrae variables. In addition, because of their location in a CMD, they are at least 3 magnitudes brighter than the oldest's MSTOs and thus much easily detected. The detection of RR Lyrae stars is presently one of the only ways to confirm the existence of an ancient stellar population in galaxies for which the oldest MSTOs are not observed.

1.3 M32: a unique window on the stellar populations of elliptical galaxies

The Local Group elliptical galaxy M32, first catalogued by C. Messier in the 1770s, is the subject of study in this thesis. It is a small satellite of M31 projected onto its minor-axis disk, and only 24 arcmin from its nucleus. Due to its low luminosity, compactness and high surface brightness (Bender et al. 1992), M32 is classified as a compact elliptical (cE) galaxy, cE2. M32 is the prototype of this class of ellipticals, consisting of ~ 20 galaxies known so far (Davidge 1991; Ziegler & Bender 1998; Chilingarian et al. 2009), the so-called M32-like galaxies.

Despite the fact that M32 has been extensively observed and studied, its SFH, and therefore its origins, are still a matter of debate. The proposed models for M32's origins span a wide range of hypotheses: from a true elliptical galaxy at the lower extreme of the mass sequence (e.g., Faber 1973; Nieto & Prugniel 1987; Kormendy et al. 2009) to an early-type spiral galaxy whose concentrated bulge, unlike its disk, still survives the tidal stripping process caused by its interactions with M31 (e.g., Bekki et al. 2001; Chilingarian et al. 2009). There has been suggestions that the observed compact nature of M32 is the consequence of tidal pruning (e.g., Faber 1973; Burkert 1994; Bekki et al. 2001), due to the interactions of M32 with M31. However, such a scenario is in disagreement with the findings of Nieto & Prugniel (1987) and Choi et al. (2002) who concluded that M32's precursor, i.e. before being accreted by M31, was likely to be intrinsically compact. It is interesting to note that M32 does not appear to possess globular clusters (even though it is supposed to have a number between 10 and 20, van den Bergh 2000) which supports the hypothesis that M32 has been tidally stripped by M31.

Regardless of its origins, M32 is *today* an elliptical galaxy and the nearest system that has properties very similar to the giant ellipticals: it falls at the lower luminosity end of all of the structural and spectroscopy scaling relations of giant ellipticals: the Faber–Jackson relation (e.g., Faber & Jackson 1976), the Kormendy relation (e.g., Kormendy 1985), the mass–age–metallicity and $[\alpha/\mathrm{Fe}]$–mass relationships (Trager et al. 2000a), and the Mg–σ relation and the Fundamental Plane of early-type galaxies (e.g., Bender et al. 1992), as shown in Fig. 1.1, where M32's location is indicated. More recently, K09 find that both central and global parameter correlations place M32 as a normal, low-luminosity elliptical galaxy in all regards (see Fig. 1.2). K09 confirmed the results from a pioneering work by Wirth & Gallagher (1984), as well as those from e.g. Sandage et al. (1985a,b), Kormendy (1985, 1987), who suggested that compact ellipticals like M32 are not (as previously thought) diffuse "spheroidals" (or dwarfs) like NGC205, but instead are the extension to low luminosities of the family of giant ellipticals.

Given its proximity, M32 provides a unique window on the stellar composition of elliptical galaxies, since it can be studied by both its integrated spectrum and the photometry of its resolved stars. While we note that the SFH of a low luminosity elliptical such as M32 ($r_{\rm eff} \approx 40''$, Choi et al. 2002; Kormendy et al. 2009) may differ from those of giant ellipticals, it is a fact that in general models applied to giant ellipticals reach the same conclusions as those applied to M32 (e.g., Worthey 1998). M32 is therefore a vital laboratory to test the applicability of the stellar population models to more distant galaxies, since it provides the possibility of comparing predictions from the spectroscopic analysis of integrated light with the resolved stellar content. In what follows we discuss M32's stellar populations as revealed by unresolved and resolved stellar population studies.

1.3.1 Results from spectroscopic studies

From spectroscopic studies, one of the most important results of synthetic population models was found by O'Connell (1980): models fail to reproduce M32 with a single old-age and solar-metallicity population. Various synthetic population models have claimed that M32 underwent a period of significant star formation in the recent past, i.e. about 5–8 Gyr ago, (e.g., O'Connell 1980; Pickles 1985; Bica et al. 1990) based on the presence of enhanced Hβ absorption in the integrated spectrum of M32, and thus indicate signatures of an intermediate luminosity-weighted age population (e.g., Rose 1994; Trager et al. 2000a; Worthey 2004; Schiavon et al. 2004; Rose et al. 2005; Coelho et al. 2009). Rose et al. (2005) studied the nuclear spectrum of M32 and found radial gradients in both the age and metallicity of the luminosity-weighted mean stellar population of M32: the population at $1\ r_{\rm eff}$ is ~ 3 Gyr older and more metal poor by ~ -0.25 dex than the central population, which has a luminosity-weighted age of $\sim$ 4 Gyr and [Fe/H] ~ 0.0. Extrapolation of the spatially resolved spectroscopy of González (1993) results in an average age and metallicity of M32 at $1'$ from its center of 8 Gyr old and [Fe/H] ~ -0.25 (Grillmair et al. 1996b; Trager et al. 2000a). This is consistent with a more recent estimate by Worthey (2004) who found the age of M32 at $1'$ to be 10 Gyr old. The most recent results from stellar population models are given by Coelho et al. (2009) who observed high signal-to-noise spectra at three different radii, from the nucleus of M32 out to $\sim 2'$ from the center of M32. They propose that an ancient and intermediate-age population are both present in M32 and that the contribution from the intermediate-age population is larger at the nuclear region. They claim that a young population is present at all radii (see also e.g., Trager et al. 2000a; Rose 1985, 1994; Schiavon et al. 2004), but its origin is unclear. Moreover, the determination of ages in integrated spectra is a difficult problem, as extended horizontal branch morphologies and/or blue stragglers, unaccounted for in the models, can mimic younger ages (e.g., Burstein et al. 1984; Rose 1985; de Freitas Pacheco & Barbuy 1995; Maraston & Thomas 2000; Trager et al. 2005). Thus, lacking any direct evidence for such a young population (ages < 1 Gyr), and due to the uncertainties in the synthesis models, these results should be considered with some caution.

1.3.2 Results from resolved stars studies

Due to the M32's high surface brightness and its projected position onto the disk of M31, crowding and contamination by M31's stars* have always made difficult to study the individual stars of M32. Indeed, after the work by Baade (1944), no studies on the resolved stellar content of M32 have been undertaken for several years until the work by Freedman in 1989. During the last two decades, thanks to the power and resolution of new generations of telescopes and detectors, and especially with the advent of the HST, observations of individual stars in M32 have increased. Photometric studies of resolved stars have supported the existence of an intermediate-age population (e.g. Freedman 1992a; Davidge & Jensen 2007) by detecting AGB stars suggestive of a ~ 3 Gyr old population. However, observations by Davidge & Jensen (2007), obtained with the NIRI imager on the Gemini North telescope, do not support spectroscopic studies that find an age gradient in M32, since they suggest that the AGB stars and their progenitors are smoothly mixed throughout the main body of the galaxy. In Brown et al. (2000, 2008), using ultraviolet observations of the center of M32, and in Chapter 4 of this thesis, using the ACS/HRC data presented here, evidence of an ancient, metal-poor population have been found by observing hot horizontal branch and RR Lyrae stars, respectively. Worthey et al. (2004), using optical observations obtained with the Wide Field Planetary Camera 2 (WFPC2) on board HST and presented by Alonso-García et al. (2004), studied the stellar populations of the outer regions of M32 and M31 and found that there is no trace of a main sequence younger than ~ 1 Gyr in M32 at a region $7\ r_{\rm eff}$ from its center. The most extensive study of the resolved stellar populations of M32 has been carried out by Grillmair et al. (1996, hereafter G96), who resolved individual stars down to slightly below the level of the HB with the HST WFPC2 in a region of 1–$2'$ from the center of the galaxy (see Fig. 1.5). Their most important result is the composite nature of the CMD of M32. They concluded that the wide spread in color of the giant stars in their CMD cannot be explained only by a spread in age but rather by a wide spread in metallicity. However, given the age–metallicity degeneracy on the giant branch, there may well be a mixture of ages present in their field, but age effects are less important than metallicity on the giant branch morphology. For an assumed age of 8.5 Gyr old, the metallicity distribution function has a peak at $[\mathrm{Fe/H}] \sim -0.25$, consistent with the extrapolation made from the spatially resolved spectroscopy of González (1993). The spread

* An especially problematic aspect of this contamination is that the mean metallicity of stars in the outer disk of M31 is not extremely different from that of the outer regions of M32, and thus the photometric properties of stars in M32 and the disk of M31 overlap significantly.

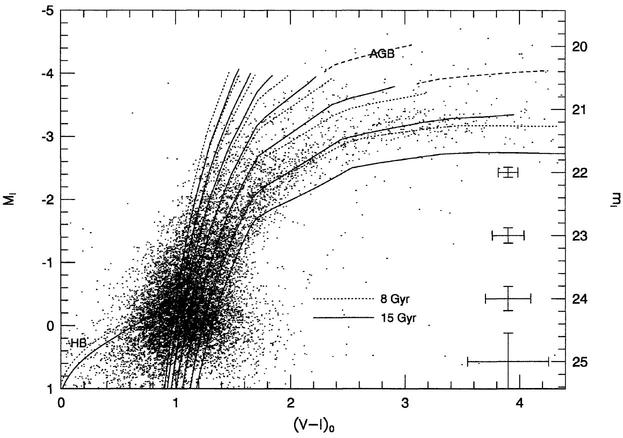

Figure 1.5: CMD of stars in M32 presented by Grillmair et al. (1996b) from HST/WFPC2 observations. Theoretical isochrones from Worthey (1994) are superimposed for [Fe/H] between -1.2 and 0.0 in 0.2 dex steps, and ages of 8 Gyr (dotted lines) and 15 Gyr (solid lines). An intrinsic spread in metallicity is clearly observed. The hypothetical locations of HB and AGB stars are indicated.

in metallicity found by G96 ranges from roughly solar to below -1 dex. This study, as well as those by Brown et al., Alonso-Garcia et al. and Worthey et al., concluded that the metal-poor population is insignificant, contrary to the results of Coelho et al. (2009). Finally, a young population of $\lesssim 1$ Gyr claimed by several population models to be present in the spectrum of M32 has not been seen by any of the observations of resolved stars. Overall, the photometric studies carried out so far only obtained information from the brighter stars of M32, i.e., the upper CMD. These studies were prevented from observing fainter stars by the extreme crowding of M32. Since upper giant-branch tracks are degenerate in age and metallicity, much like integrated colors and metallic lines, it is not possible to derive an age from the upper CMD alone as above-mentioned.

1.4 This Thesis

As discussed above, models of the integrated light from stellar populations that are fundamental to study the formation and evolution of elliptical galaxies have become very sophisticated, and there is now a better understanding of how to interpret their results in terms of the average properties of a galaxy. However, these models still suffer from uncertainties: e.g., it is difficult to distinguish between a young or hot old population since the latter is not necessarily accounted for in the models (Maraston & Thomas 2000). Therefore, there is a pressing need for them to be tested with direct observations of stars of an actual elliptical galaxy. M32, although a low-luminosity elliptical, is the nearest system with structural properties reminiscent of giant ellipticals (see K09 and references therein). Given its proximity, M32 provides a unique window on the stellar composition of elliptical galaxies since it can be studied by both its integrated spectrum and the photometry of its resolved stars. Thus, it is a vital laboratory for stellar population models. To date, there has not been a consistent comparison between predictions from the spectroscopic analysis of its integrated light and its resolved stellar content. Moreover, the SFH of M32 is still a matter of debate. In this thesis, we investigate the resolved stellar populations of M32 with the primary goal of deriving a complete SFH of this enigmatic galaxy.

The only way to derive the SFH of M32 and to test conclusions so far based solely on integrated colors and spectral indices is to obtain deep CMDs that reach the MSTOs. Moreover, a deep CMD and luminosity function of M32 can be used as the basis for spectral synthesis studies. An agreement between observed and synthetic indices for M32 would confirm such indices as simple diagnostic tools for constraining stellar populations in integrated light of other elliptical galaxies, for which only the integrated light is available given their greater distances. Furthermore, the CMD allows for the study of spreads about mean properties in a way that is currently impossible with integrated light. These spreads are as important as the mean values in decoding the SFH of the galaxy.

We were awarded 64 orbits of the HST to observe the MSTO of M32 with the High Resolution Channel (HRC) of the Advanced Camera for Surveys (ACS). The proximity of M32, combined with the high resolution images of HST ACS/HRC, allows for a remarkable improvement in our study of M32's stellar content. Furthermore, the results of this thesis represent the most complete inventory to date of M32's stellar populations and provides a rich data base to compare with unresolved stellar population models. This is fundamental to test the applicability of stellar population models to distant elliptical galaxies.

1.4.1 Outline of the thesis

In Chapter 2 we introduce our new HST observations of two fields near M32 and present the deepest optical CMD of M32 so far obtained. This CMD reaches more than 2 mag fainter than the previous optical CMD by G96 (compare Figs 1.5 and 2.12) and fully resolves the RGB and the AGB. One of its main features is a strong RC. We report the discovery of a blue plume (BP), consisting of young stars and/or blue straggler stars (BSSs), not claimed to have been observed before. We also detect for the first time in M32 an RGB bump and an AGB bump. The CMD locations of the bumps together with the RC allows to constrain the ages and metallicities of M32 at our field's location. We obtain the photometric metallicity distribution function and the luminosity function of M32. By analyzing the obtained CMD, we have achieved the most comprehensive photometric study of the resolved stellar content of M32 to date. We have found that M32 is dominated by intermediate-age and old (8–10 Gyr old), metal-rich ($[\mathrm{Fe/H}] \sim -0.2$) stars and it contains some old (> 10 Gyr), metal-poor stars ($[\mathrm{Fe/H}] \sim -1.6$) as well as possible young populations (0.5 – 2 Gyr old stars). We also qualitatively analyze the CMD of our M31 background field and find that it contains older and more metal-poor stellar populations than M32.

Chapter 3 follows-up the analysis presented in the previous chapter. We present a quantitative analysis of the mix of ages and metallicities in the fields observed using the above-mentioned synthetic CMD method. Since the oldest MSTOs of the galaxy are not reached in our observations, we are not be able to obtain a complete SFH from this CMD. Nonetheless, from a more sophisticated analysis of the CMDs presented in Chapter 2, we derive a detailed young and intermediate-age SFH of M32 at $\sim 2'$ and M31 at our background field's location. We find that M32 has a substantial population of 2–5 Gyr old stars contributing to $\sim 42\%$ of its mass at our field's location, an unexpectedly large population of young stars for an elliptical galaxy at such a large distance from its center. M31, on the other hand, is predominantly old at our background field's position.

In Chapter 4 we present newly-detected RR Lyrae variables obtained with our observations. Due to the severe crowding in our fields, even with the high spatial resolution of HRC it is not possible to reach the MSTO with sufficient precision to claim the presence of a very old population. Thus the detection of RR Lyrae stars in M32 is presently the only way to confirm the existence of an ancient stellar population in this galaxy. We detected 17 RR Lyrae variables in the M32 field and 14 in our M31 background field, from which a 1-sigma upper limit of 6 RR Lyrae variables belonging to M32 could be determined. We used in addition our two ACS/WFC parallel fields to provide a better constraint on the M31 background, and we have obtained that 7^{+4}_{-3} (68% confidence interval) RR Lyrae variables in our M32 field belong to M32. We have therefore found evidence for an ancient population in this galaxy. The RR Lyrae stars in both our primary M32 and M31 background fields have indistinguishable mean V-band magnitudes, mean periods, distributions in the Bailey diagram and ratios of RRc to RR(tot) types.

In Chapter 5 we summarize our main results and conclude by discussing some follow up studies based on this work.